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FINAL REPORT FOR NAGW-740 (SMM GUEST INVESTIGATOR PROGRAM)

What follows is the final report for NASA grant NAGW-740, awarded in the 1984-1985 Guest Investigator Program of the Solar Maximum Mission.

The title of the research proposal was, "Exploration of the solar-stellar connection at high spectral resolution with the Ultraviolet Spectrometer and Polarimeter, and studies of thermal bifurcation at the photosphere-chromosphere interface". The objectives of the proposal fell into two areas: (1) to compare the dynamics of high-excitation plasma in the 10^5 K *transition zones* of stars of late spectral type, as observed with the *International Ultraviolet Explorer*, with the radial gas velocities of individual structural features of the solar TZ, as observed with high spatial resolution by the UVSP on the SMM; (2) to study the 4th-positive system of carbon monoxide in the quiet Sun and in active regions in order to explore the properties of thermal inhomogeneities at the critical interface between the photosphere and chromosphere.

The Solar-Stellar Connection: Redshifts and Flux-Flux Diagrams

The first part of the program primarily was archival in nature: no new observations were proposed aside from a small study of the H I Lyα emission feature. Unfortunately, the failure of the UVSP grating drive shortly after the proposal was funded in the spring of 1985 prevented those observations from being obtained. On the other hand, the comparative study of solar and stellar velocity fields in the spirit of the solar-stellar connection *was* completed recently.

I, and my collaborators E. Jensen and O. Engvold (Institute for Theoretical Astrophysics, University of Oslo), submitted to the *Astrophysical Journal Supplement* a long paper entitled: "Redshifts of high-temperature emission lines in the far-ultraviolet spectra of late-type stars. II. New, precise measurements of dwarfs and giants." In that work, we obtained a series of high-quality far-ultraviolet spectrograms of four 'solar-type' dwarf stars using the *IUE*. The stars ranged in "activity" level from "quiet" (very comparable to the Sun) to "active" (chromospheric surface fluxes some 5-10$\times$ solar). We carefully measured the Doppler shifts of the high-excitation doublets of Si IV ($\lambda\lambda$1393.8,1402.8) and C IV ($\lambda\lambda$1548.2,1550.8), and obtained a mean *redshift* of these features of $+6$ km s^{-1} over the sample of four stars

(NASA-CR-181295) EXPLORATION OF THE SOLAR-STELLAR CONNECTION AT HIGH SPECTRAL RESOLUTION WITH THE ULTRAVIOLET SPECTROMETER AND POLARIMETER, AND STUDIES OF THERMAL BIFURCATION AT THE (Colorado Univ.) 7 p
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(there were statistically-significant redshifts detected in each star individually, and little apparent variation from star to star). The mean redshift for the stellar sample is intermediate to that expected for quiet areas on the Sun and for magnetic active regions (based on UVSP observations – primarily of C IV – analyzed by J. Klimchuk for his thesis at Colorado), if observed as a disk-average ("Sun as a star"). The similarity of the stellar result to the average solar value of the high-excitation redshifts – and the detection of large redshifts in evolved subgiants and giants of late spectral type – gives us some encouragement that gas-dynamic processes of the solar atmosphere must occur ubiquitously in the cool-half of the Hertzsprung-Russell diagram, and therefore probably reflect a universal consequence of surface magnetic activity, rather than an accidental manifestation on our nearby star. Nevertheless, the large variation of downflow velocities seen between quiet and active regions on the Sun, but lack of such a dispersion between the two 'quiet' and two 'active' dwarfs of the stellar sample, is cause for some concern: a proper resolution of the issue will require higher-dispersion spectroscopy than can be obtained with the *IUE*, namely the HRS of the Hubble Space Telescope. A preliminary description of the project was presented at the "Advanced Solar Observatory Workshop", held in January 1985 in Carmel, California.

Other aspects of the first part of the proposal – comparative studies of Lyα emission in solar-type stars and the Sun; and comparisons of "flux-flux" diagrams for important chromospheric and transition-zone emissions – have not been completed as yet. I, and a graduate student J. Bennett, have compiled an extensive list of *IUE* line fluxes for a sample of 600 late-type stars (about 100 of which are of solar type), as well as an extensive series of line fluxes for the disk-average Sun (observed at comparable spectral resolution to the *IUE* low-dispersion mode) from the *Solar Mesosphere Explorer*. What needs to be done to complete this portion of the project is to compile a series of flux-flux diagrams for *individual* structural features of the solar atmosphere in order to create a *context* within which to analyze the stellar – and disk-average solar – observations. This portion of the project involves a great deal of detailed work with the UVSP data set, and will be accomplished by Bennett and C. Schrijver as a part of a SADAP project proposed by Schrijver.

Thermal Bifurcation at the Photosphere-Chromosphere Interface

The second major part of the proposal – the study of "thermal bifurcation" at the photosphere-chromosphere interface – was intended to be based almost solely on new observations with the UVSP. Although the failure of the grating drive severely limited the scope of the observing program, a series of preliminary spectra were obtained in late 1984 and early 1985 (thanks to R. Shine) prior to the hardware failure. Earlier this year, I finally was able to install a copy of the UVSP data system (using the IDL command language) at my home institution, and thereby was able to receive and analyze the ≈ 30 spectral scans that Dick Shine had taken.

The most extensive portion of the data set involved long integrations of a ≈ 5 Å-wide spectral region including the C IV doublet. I measured a series of reference Si I emission features in each spectrum, and fitted their apparent positions with a polynomial dispersion relation in order to calibrate the individual wavelength scales. I then interpolated each scan onto a common wavelength scale, and coadded the scans in three groups according to heliocentric angle: $\mu \approx 1.0$ (disk center), 0.4, and 0.2 (close to the limb). The coaddition improves the signal-to-noise ratios, and averages – to some extent – over different types of "quiet-Sun" structures that might have been intercepted by the $180''$-long slit used in the UVSP observations. Figure 1, below, illustrates the processed spectra at the three heliocentric angles: the tracings emphasize the weak spectral structure in the vicinity of C IV $\lambda\lambda$1548.2,1550.8. Each intensity spectrum was normalized to a 'continuum' flux measured in a 0.3 Å band at 1549.35 Å.

The numerous Si I emissions used to calibrate the wavelength scales (vertical dotted lines indicate the laboratory wavelengths) dominate the spectral interval, aside from the extremely prominent C IV doublet (reduced by a factor of 20 in the insert sections). One notices that the C IV features are slightly *redshifted* relative to the reference Si I emissions at disk center, and are slightly *blueshifted* near the limb. The approximate net Doppler shift between disk center and the limb is about 70 mÅ– 14 km s^{-1} – typical of the values obtained by Jim Klimchuk in his thesis.

Most of the emissions in the interval exhibit prominent brightening towards the limb, relative to the λ1549.35 continuum. Only one feature clearly is an exception: λ1549.1 (vertical line of connected dots). The feature is coincident in wavelength with the 0–0 Q24 line of the CO 4th-positive system, which can be radiatively pumped by one of the components of the C I λ1657 multiplet owing to a spectral overlap with the 0–2 Q24 line. All of the other CO lines in this interval which can be fluoresced by C I through the 0−2 band are blended with Si I emissions or with the C IV components. Previous studies of CO fluorescence (i.e., Bartoe *et al. Ap. J. Letters*, **223**, L51 [1978]) based on HRTS sounding rocket spectra identified many more "CO" lines in this interval: many of the identifications, at least in the quiet Sun, likely are spurious due to coincidences with the Si I emissions.

I also searched for evidence of CO *absorption* features in the vicinity of the C IV lines: the center-to-limb behavior of the molecular absorptions are useful diagnostics for the existence of cool material at "chromospheric" altitudes identified in low-spatial-resolution studies of the fundamental vibration-rotation bands of CO in the mid-IR (4.7 μm). The far-UV CO lines have the advantage that they should respond *exponentially* to temperature, and thus exhibit higher intensity contrasts than the more linear response of the mid-IR CO absorptions. Nevertheless, I was not able to convincingly identify any CO 4th-positive system absorptions in the 1547-1551 Å region. There appear to be weak absorptions in the 1549-1551 Å "continuum" region at disk center which qualitatively agree with the 0−0 Q25-26, R30-32, and P20-22 lines. However, given the large frequency of occurrence of emission lines in the far-UV, it is difficult to conclusively identify structure due to true absorption processes, at least with the existing spectral material. If the grating drive on the UVSP had not failed, I would have been able to obtain follow-up observations of these features to confirm the proposed identifications. Possibly, there are additional long-slit observations of the C IV region in the UVSP data archive which might bear on the question of the identification of the CO absorptions, but I have not yet pursued that possibility.

Of course, identifying spectral features represents only the beginning of a proper analysis. The fluoresced CO features are formed by the optical pumping of relatively cool gas – where the molecules are abundant – by radiation emitted from the hot gas of the mechanically-heated "chromosphere". In the conventional picture, the chromosphere overlies the relatively cool layers at the top of the photosphere (the so-called *temperature minimum region*), and thus the CO is radiatively excited by downward propagating radiation from above. In a less conventional picture – developed in part from observations of the infrared bands of CO – cool gas can exist at relative high altitudes in the solar atmosphere, at levels usually associated exclusively with the hot chromosphere. In fact, in the "thermal bifurcation" model I, and my collaborators, devised several years ago, fairly cold gas (T$\approx$ 3500° K) is *pervasive* in the chromosphere, and the classical, hot chromosphere proper is confined to discrete structures – like magnetic "flux tubes" – of comparatively small horizontal extent (covering only $\approx$ 10% of the surface in the quiet Sun, for example). In the thermal bifurcation scenario, the CO lines would be fluoresced by *horizontal* diffusion of radiation away from the chromospheric structures. The fact that the fluoresced CO 0–0 Q24 feature exhibits a significantly different center-to-limb behavior than the chromospheric Si I emissions likely is attributable to the geometry of the radiative pumping. However, whether the apparent center-to-limb behavior favors the plane-parallel interface between chromosphere and photosphere of the conventional picture, or the essentially *horizontal* interfaces of the highly inhomogeneous thermal-bifurcation scenario, must be answered by detailed model simulations. The resolution of this question is essential to understanding the energetics of the chromosphere, and in fact bears strongly on the interpretation of the fluorescence of carbon monoxide in other stars, particularly the red giants. Therefore, an important component of the proposed project – the theoretical modelling of the CO fluorescence – remains unfinished. Nevertheless, I currently am undertaking ground-based observations of the violet system of cyanogen (CN) near 3883 Å: the high-spatial-resolution pictures of CN "bright points" (which coincide with hot structures devoid of the molecules) should provide important limits on the surface coverage of chromospheric material and thereby help in the proper formulation of the geometry of the CO fluorescence problem.

Concluding Remarks

The original project I intended to undertake very much depended on an interactive exploration of specific parts of the solar far-UV spectrum with the UVSP – the highest quality, photon-counting spectrometer that has yet been applied to solar problems. Unfortunately, due to the failure of the grating drive mechanism, I was able to undertake only the initial steps of that exploration: namely, to identify the presence of possibly important spectral structure. The critical follow-on observations then became impossible; and the initial results thus remain tantalizing but not definitive. I hesitate to publish these results without independent evidence that the proposed identification of the (single) fluoresced CO feature truly is reasonable: I could publish a criticism of the "discovery" work on CO fluorescence of nearly a decade ago – those authors certainly misidentified a number of "CO" features in their quiet-Sun spectra – but such a paper would not be very useful, in my opinion.

In short, although the "redshift" part of the proposal has been completed successfully, the "thermal bifurcation" part is very much unfinished. I had hoped that the latter would have involved an ongoing observing program with the UVSP, including the eventual development of theoretical models, but the present "monochromatic" capabilities of the UVSP put an end to that hope. Unfortunately, the way things have been going vis-a-vis solar high-resolution far-ultraviolet spectroscopy, there is little prospect that I will be able to acquire additional observations relevant to the project before the end of the century. Thus, the prospects for truly understanding the fluorescence of CO in the far-UV hinges on the possible existence of appropriate spectral material in the archives of the UVSP. I have not yet explored this possibility, but intend to do so in the near future.

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Boulder, Colorado

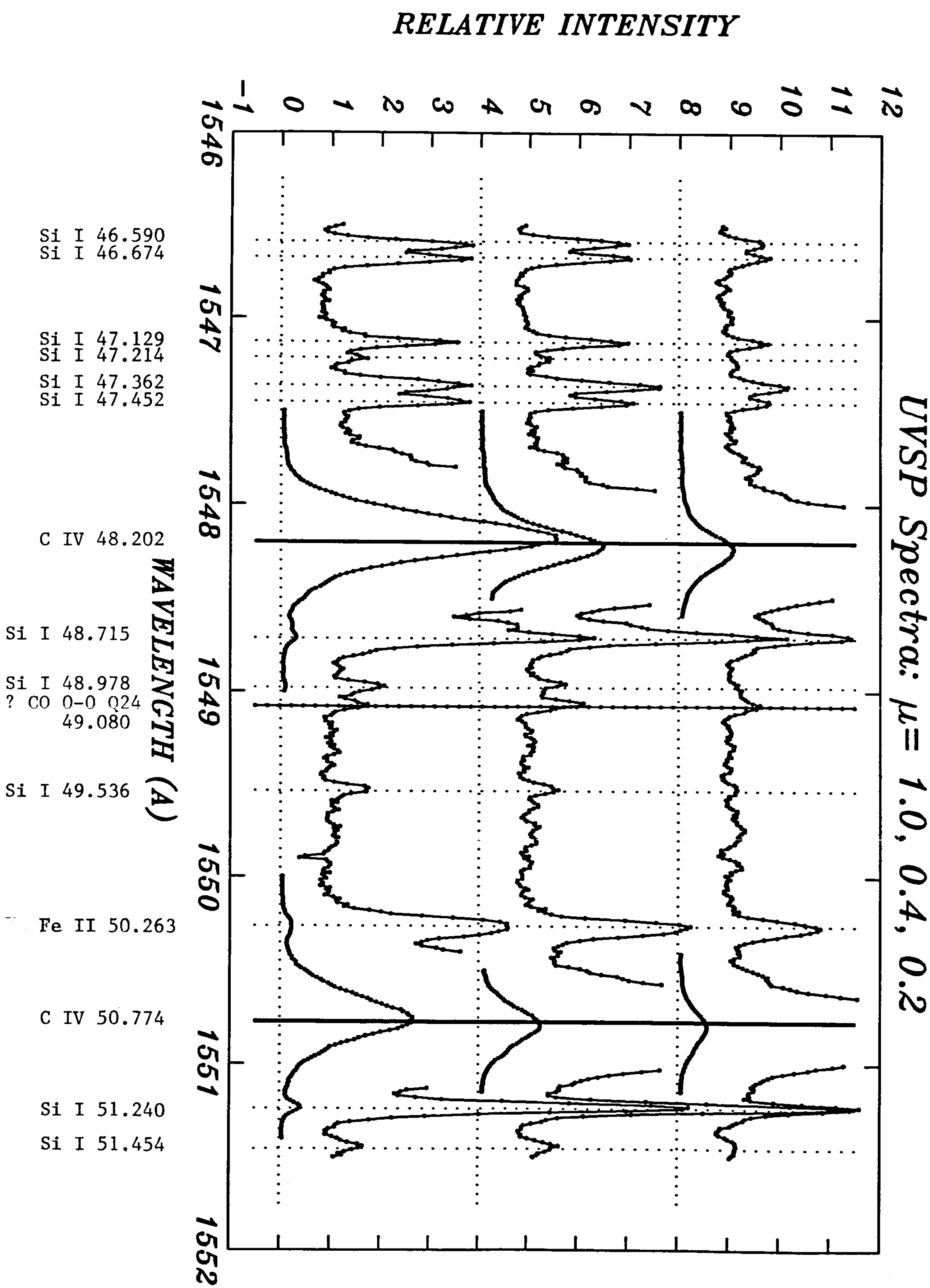

Figure 1. UVSP spectra of the C IV doublet.